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Analysis of Multiresource Production for National Assessments and Appraisals

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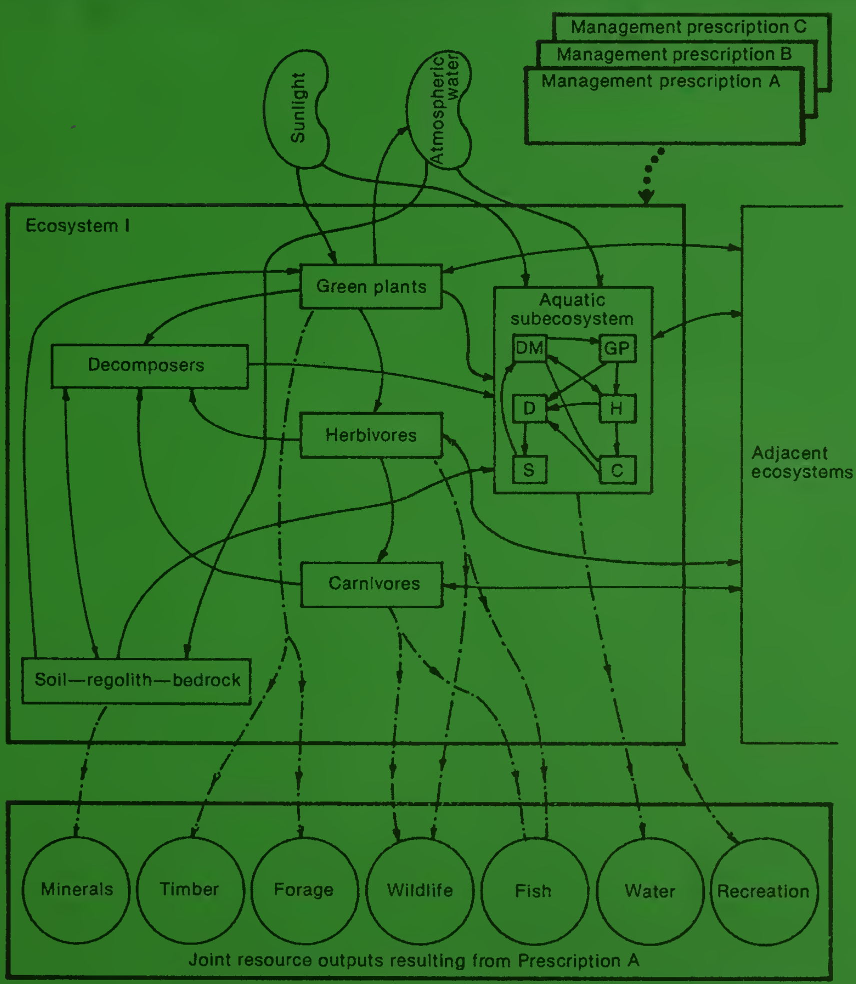

Abstract

This report gives an overview of the analytical methods used in integrated (multidisciplinary, multiresource, and multilevel) land management production analyses. The ecological and economic theory underlying both simulation and optimization methods are also reviewed.

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MANAGEMENT IMPLICATIONS

The dominant approach in integrated resource production analysis is optimization modeling, specifically multiresource linear programming modeling. Tradeoffs between alternative resource production strategies can be examined under a variety of decision criteria in these models. The theoretical basis for this approach is well-founded in the economic theory of production. The successful use of these models presumes the availability of benefit/cost information from supply/demand models, and the availability of production capability/response information from ecological models. Because this review focuses only on the production side of integrated resource analysis, it does not consider the availability of benefit/cost information.

There is no commonly accepted, ecological technique to analyze the simultaneous production of natural resources applicable in all ecosystems. Production capability/response information must be determined for the optimization models quantitatively for each resource, with the integration being qualitative. Advances in ecological research are increasing the degree to which the production capability/response relationship can be quantified. Resource analysts must select the appropriate analytical technique for their specific management problems.

The recent work of Wong (1980) in hierarchial modeling suggests promising ways to include multilevel considerations into integrated resource production analyses.

INTRODUCTION

National assessments of forests, range lands, agricultural lands, and associated waters of the United States are required by law. These assessments must be multidisciplinary, multiresource, and multilevel. This report is an overview of the analytical techniques used in integrated land management analyses, where integrated includes multidisciplinary, multiresource, and multilevel considerations.

Assessments, appraisals, and inventories are required by a number of laws. An assessment of renewable resources on forests and rangelands is required by the Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA)[2] as amended by the National Forest Management Act of 1976 (NFMA)[3]. Appraisals of the soil, water, and related resources are required by the Soil and Water Resources Conservation Act of 1977 (RCA)[4]. Adequate inventories and documentation for development of policies and management of the nation's federal lands are required by the Federal Land Policy and Management Act of 1976 (FLPMA)[5]. The Multiple Use-Sustained Yield Act of 1960 (MU-SY)[6] requires joint consideration of the major outputs from the national forests. Accounting for the environmental impact of management is required by the National Environmental Policy Act of 1969 (NEPA)[7]. The RPA, as amended by the NFMA, requires that these assessments be coordinated with the requirements of the Renewable Resource Research Act, Cooperative Forestry Assistance Act, and the Public Rangelands Improvement Act.

Natural resource outputs, such as timber, wildlife, etc., can be analyzed in several different frameworks. Resource outputs can be examined functionally in terms of timber, range, wildlife, etc., or they can be examined in a multiresource context. They can be evaluated in ecological terms, economic terms, or sociological terms. Resource outputs can be analyzed at the level of the forest, the region, or the nation. Current production of resource outputs can be assessed, and projected trends of the current production can be made, or alternatives for future production possibilities can be projected.

Analytical techniques have been developed to integrate these different tasks specified by law and these different analytical frameworks. Optimization models are one method used to integrate multiresource, multidisciplinary, and future-oriented considerations. These optimization models require as input predictions about future conditions, which are developed from ecological and economic simulation models. Specifically, supply/demand models can provide benefit/cost (economic) information, and ecological analyses can provide production capability/response information. Social analysis models can predict the social impacts of the solutions given by optimization models.

Optimization models are the dominant integrated analytical technique, because they provide a framework for a quantitative analysis of resource production in an economic and biological environment. Other integrated approaches have not provided such a framework for integrating inputs from ecological, economic, and social analyses that is consistent with the currently accepted perspectives in ecology, economics, and social analysis.

[2]Public Law 93-378. United States Statutes at Large. Volume 88, p. 476 (Pub. L. No. 93-378, 88 Stat. 476).
[3]Pub. L. No. 94-588, 90 Stat. 2949.
[4]Pub. L. No. 95-192, 91 Stat. 1407.
[5]Pub. L. No. 94-579, 90 Stat. 2743.
[6]74 Stat 215, as amended; 16 U.S.C. 528-531.
[7]Pub. L. No. 91-190, 83 Stat. 852.

This report focuses on the production or supply side of integrated resource analysis. The theory underlying the ecological and economic analyses is reviewed first. This presentation of ecological analyses reflects the state-of-the-art in its concentration on those theoretical approaches which have been applied in a limited number of cases. There is no commonly accepted ecological technique to analyze the simultaneous production of natural resources in an ecosystem. In contrast, there are standard analytical techniques to analyze the production of natural resources in an economic framework. These techniques have been expanded to analyze multiresource production. These multiresource optimization modeling techniques are reviewed last, and include a review of those techniques which attempt to include multilevel considerations.

ECOLOGICAL ANALYSES OF PRODUCTION

Land management activities affect the structure and function of an ecosystem. Changes in the ecosystem cause changes in resource outputs (fig. 1). Analytical techniques predicting single resource production quantify those pathways in figure 1 pertaining to the single resource, such as timber or wildlife. A consideration of the impact of this single resource management on other pathways, and the joint production of resource outputs is necessary to evaluate the impact of management on the ecosystem. This is often done intuitively by managers in the field. The problem is quantifying the interaction of these pathways. Quantitative techniques

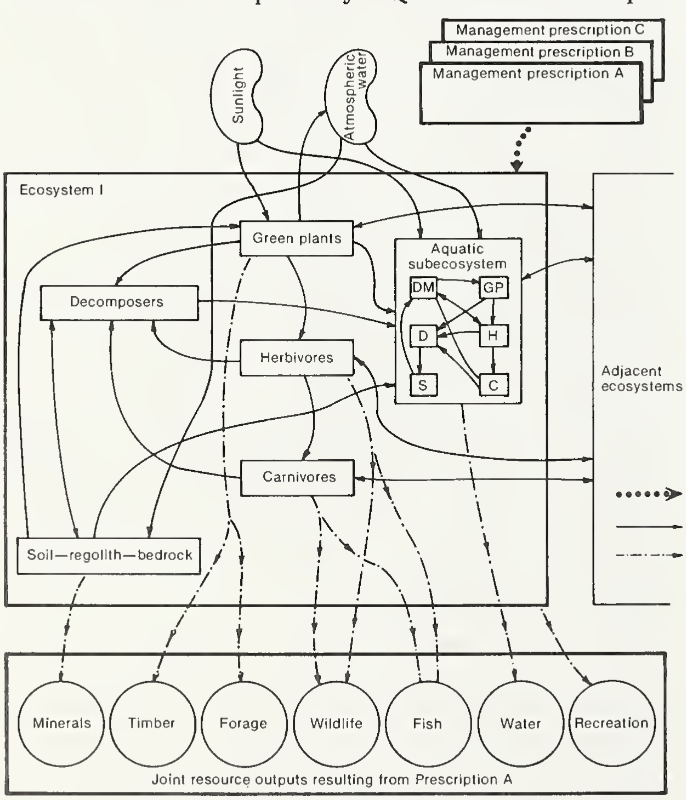

Figure 1.—Management prescriptions, ecosystem structure, and resource outputs.

predicting the production of natural resources have generally focused on single resource outputs (Alig et al. 1983, Hawkes et al. 1983, and Mitchell 1983).

Analysis of joint production using an ecosystem approach to natural resource management is relatively recent (Van Dyne 1969), and quantitative techniques are in early stages of development. Progress in this area has been hampered by insufficient and inadequate data, and by lack of ecological theory. Long-term records of ecosystem response to management under controlled conditions are rare. Although advances in ecological theory continue to be made, there is no single, unifying theory about ecosystem structure and function that could be applied to all ecosystems.

This review focuses on those theoretical ecological analyses which have been used to examine the impact of management. Different approaches in ecological research have increased understanding of ecosystem functioning, and this understanding has been used to examine the impact of management on the ecosystem's productive capacity. Ecosystem-level models, such as the large-scale simulation models of the International Biological Program, attempt to quantify all pertinent aspects of the ecosystem and track the impacts of management on the entire system. Another approach has been to quantify attributes of the ecosystem which could act as indicators of ecosystem health. When the complexities become too great to quantify, more intuitive approaches, such as an interdisciplinary team, have been used to estimate the impact of management. Because of the diversity of approaches, the resource analyst must select that technique which best describes the impact of the particular management activity being considered.

Ecosystem Theory

Ecologists have struggled to define a theoretical structure for ecological research (Haug 1981), and these continuing struggles approach the problem from two directions. The first approach views the ecosystem as a system and attempts to define a general theory of ecosystem behavior applicable to all types of ecosystems. The theoretical work of Miller (1978) is an appropriate example of this category. The second approach focuses on attributes of the ecosystem and attempts to define the relationships of the parts in order to describe the whole. Large-scale simulation models, such as the shortgrass prairie model, ELM (Innis 1978), are examples of this approach.

Ecosystem Approaches

Ecosystem-level theories represent frameworks integrating ecosystem structure and function. The approaches differ in their theoretical assumptions and their degree of quantification. Examples of these ecosystem-level theories include: the system dynamics approach of Gutierrez and Fey (1980), the living systems theory of Miller (1978), the linear modeling approaches

of Patten (1975, 1976), and the energy analysis of H. T. Odum (1971). Further development of these theories may suggest a unifying theoretical framework for the analysis of joint production in an ecosystem. Currently, some of these approaches (H. T. Odum 1971) are being applied to natural resource problems and have provided valuable information to planners (Littlejohn 1977). Because of the success of H. T. Odum's (1971) approach, it is briefly summarized.

H. T. Odum and co-workers at the University of Florida state that all systems obey three laws of energy. The first law of thermodynamics was restated by Odum and Odum (1976) as the law of conservation of energy in an ecosystem. "The energy entering a system must be accounted for as being stored there or as flowing out" (Odum and Odum 1976). The second law of thermodynamics was restated as the law of degradation of energy. "In all processes some of the energy loses its ability to do work and is degraded in quality" (Odum and Odum 1976). To these two laws Odum and Odum (1976) added a third law, first conceptualized by Lotka in 1925. Referred to as the Maximum Power Principle, this law states, "That system survives which gets most energy and uses energy most effectively in competition with other systems." It is this third law which suggests those ecosystems survive which maximize the input of energy and use it most efficiently to meet survival needs.

The impact of channelization of the Gordon River, near Naples, Fla., was assessed using Odum's approach (Littlejohn 1977). The relationship between the changing patterns of land use and regional water regimes was quantitatively expressed, and the role of wetlands in maintaining aquifer stability was evaluated in three alternative land-use scenarios, including full development. The model demonstrated the impact of development on aquifer stability and provided opportunities to test several water management plans. The Collier County Commissioner adopted, in principle, the final contract report[8] as a development plan for the region.

Ecosystem Attributes

Many ecosystem processes have been described and mathematically modeled. Because ecology is a young science, the theoretical interpretation of each process or attribute may not be universally agreed upon, and, in fact, the significance of the attribute may be in question. Johnson (1977) presented a set of ecosystem attributes commonly recognized by ecologists. These attributes included: niche; habitat; carrying capacity; community characteristics such as diversity, trophic organization, and populations; competition; succession; resilience; growth; nutrient cycling and energy flow; and evolution.

Ecological studies have described parts of ecosystem structure and function in terms of these attributes (E. P. Odum 1971, Krebs 1972, and Ricklefs 1979). Further studies have examined the effect of ecosystem disturbance on these attributes. This understanding can then be used to examine the impact of management on the individual attributes as an indicator of the impact of management on the entire ecosystem.

A thorough review of ecosystem attributes and their numerous and diverse models is not possible here. Instead, the types of models that have been used to describe these attributes in a resource management application are briefly described.

The ecosystem attributes of habitat space and carrying capacity have been used extensively to analyze the effects of management on wildlife and fish populations. Habitat space is defined as the distributional relationship of species to environment (Johnson 1977), and the selection of a habitat has been modeled as a function of environmental pattern, competition, or population densities (Rosenzweig 1981). Carrying capacity of a species refers to that population size which is asymptotically approached when growth of a population is represented mathematically by a logistic equation. The behavior of a population around its carrying capacity varies, depending upon the population control mechanisms of that species.

Population growth is a function of interacting abiotic and biotic limiting factors (Johnson 1977), and the types of models predicting population growth are as diverse as the populations themselves. The types of models include differential equation models (May 1973), matrix models (Usher 1972), and simulation models containing several different mathematical formulations. Factors incorporated in these models include variable birth and death rates, competition, predation, density of population, and spatial complexity of the environment. Hawkes et al. (1982) reviewed this literature on models of habitat space, carrying capacity, and populations in natural resource management.

A species niche can be described as the environmental dimensions in which that species alone can exist. This would include temperature ranges, humidity and salinity ranges, and biological factors such as prey species. Based on the premise that two species cannot co-exist in exactly the same niche, species interactions are examined by measuring niche dimensions, such as bill length and width of birds. Franz and Bazzaz (1977) used the theory of niche differentiation to determine the relative impact of alternative reservoir designs on vegetation in the backwater zone of the reservoir. The occurrence of each tree species was described in a probability distribution as a function of flood frequency at each of three points along the river. These distributions characterized the ability of each species to survive and grow, given the particular frequency of flood stages at that point along the river. Changes in flood stage frequencies, resulting from each reservoir design, were simulated with each of these species distributions to determine species changes along the gradient and, thus, community impact. Recommendations were made for the design that produced the least impact in community composition.

The matter of how to describe diversity, at either the species level or the ecosystem level, has received considerable debate (Ricklefs 1979). Measurements of plant

[8]Odum, H. T., C. Littlejohn, and W. C. Huber. 1972. An environment evaluation of the Gordon River area of Naples, Florida, and the impact of development plans. Department of Environmental Engineering Sciences, University of Florida, Gainesville.

and animal species diversity provide an overall estimate of the variety or number of species (species richness) and their relative abundances (evenness of distribution). There are many sampling problems associated with field measurements of diversity, and all of the diversity indexes appear to be sensitive to these problems (Ricklefs 1979).

Hurlbert (1971) discussed the many semantic, conceptual, and technical problems associated with the measurement and interpretation of species diversity. He concluded that communities with different species compositions are not intrinsically arranged in linear order on a diversity scale. Therefore, although a diversity index may show a correlation with other properties of a community or environment, that correlation is not evidence that the index is either appropriate or useful. Similarly, two or more sets of data could have the same relative abundances of totally different species and still have identical diversity index values.

Species diversity on an island has been shown to be a function of the total land area of the island and the distance from the mainland (MacArthur and Wilson 1967) and can be viewed as an equilibrium between immigration and migration. Islands can be interpreted as units of land surrounded by a barrier such as water, or human development. Island biogeography theory has been further refined by field and mathematical simulation experiments. Shaffer (1981) outlined the implications of this theory in the determination of the minimum viable population size of a species, and various authors in Soule and Wilcox (1980) addressed the implications of this theory in the management of wildlife and the design of wildlife reserves.

Mathematical models have been developed to describe trophic structure and the impact of change on that structure. May (1973) recognized four primary features of trophic structure: the number of species involved, the nature of their interconnections, the number of connections per species, and the intensity of interactions between web members. Paine (1980) stressed the importance of the intensity of interactions between web members. According to Paine, trophic links are unequal in strength. The relative strength of interaction is partially the result of the consumer's density and partially the result of the limitation on the predation process imposed by prey size. Strong interactions can be determined experimentally by examining the impact which removing a species has on a community. Human activity has indirectly tested this theory about the importance of interaction strength, and the effect of a species reintroduction was successfully predicted from this theory (Paine 1980). Most mathematical models of food webs do not incorporate interaction strength. The importance of this concept suggests that those models that examine interaction strength will become increasingly valuable (Paine 1980).

The patterns of plant populations in succession have been theorized for all ecosystems (E. P. Odum 1971) and quantified for several ecosystems. Simulation models of plant succession exist for a variety of ecosystem types: western coniferous forest (Reed and Clark 1979); nine Montana habitat types including lodgepole pine, ponderosa pine, Douglas-fir, subalpine fir, whitebark pine, and spruce communities (Kessell and Potter 1980); Appalachian deciduous forest (Shugart and West 1977); northeastern hardwoods (Botkin et al. 1972); aspen (Cattelino et al. 1979); and grassland (Gutierrez and Fey 1980, Bledsoe and Van Dyne 1972). None of these models include wildlife or fish population changes.

Energy flow and nutrient cycling have received much study at the ecosystem level in recent years. As both nutrients and energy flow through the ecosystem, each has been used as a currency to include all ecosystem component interactions in one model.

Richey (1977) studied the phosphorus cycle of a lake using a simulation model. The model building process involved interactions with field work, where parameters suggested in the model-building process were measured in the field. Once the model was constructed, certain questions were asked of it. For example, "Is it important to know the flux as well as the concentration of phosphorus in determining its importance in a lake?" (Richey 1977). The response of the model to such questions was used to suggest further experimental work. Several simulation models of energy flow and of nutrient cycling have been used in a similar manner in other types of ecosystems.

Energy flow and nutrient cycling have also been studied to understand the effects of management on ecosystem processes. For example, a model describing the sulfur cycle of a grassland system was used to examine the effects of increased sulfur dioxide from a nearby coal-powered electricity plant (Coughenour et al. 1980).

Resilience is the ability of an ecosystem to recover from an external perturbation. Ecosystem response to perturbation is usually nonlinear and is a function of the magnitude, frequency, and type of perturbation. Quantifying this attribute has been difficult because of the inadequate understanding of the ways ecosystems respond to stress. Cooper and Zedler (1980) recognized the importance of this concept in environmental impact and incorporated it into their process, although subjectively.

Johnson (1977) included the attribute evolution in his list, and what is, perhaps, most important for natural resource models is not the process of evolution itself, but the concept that systems evolve. While the effects of evolution may take a long time to actually see, the process is going on continually. This evolutionary viewpoint is evident in Holling's (1978) work on analytical techniques for environmental impact assessment which can readily incorporate change.

Environmental Indexes

Environmental indexes synthesize information on the impact of an activity on the environment. Two general categories of indexes can be seen: (1) those indexes which synthesize several environmental measurements, such as an air pollution index, and (2) those indexes which synthesize the intuition and experience of field experts or managers, such as quality of life indexes.

Ott (1978) pointed out six basic uses of environmental indexes:

1. Resource allocation—to assist managers in allocating funds and determining priorities;
2. Ranking of locations—to assist in comparing environmental conditions at different locations;
3. Enforcement of standards—to determine whether standards are being met;
4. Trend analysis—to determine changes in environmental quality over time;
5. Public information—to inform the public about environmental conditions;
6. Scientific research—to reduce a large quantity of data to a form that gives insight to the researcher conducting a study of some environmental phenomena.

The use of environmental indexes is often contrasted with the use of a mathematical model in determining environmental impact. The construction of a mathematical model of an ecosystem may require more detailed data and theory than is currently available. Therefore, it appears more attractive to use an environmental index. Ott (1978) stressed that index development must begin with a carefully defined concept of the purpose of the index and that the original purpose must be respected when the index is used. Ott (1978) pointed out that because indexes are meant to simplify, in the process of forming an index, some information is lost. This is a problem only when the index is later used to answer a question it was not designed to address.

Cooper and Zedler (1980) proposed a regional environmental assessment process that involved mapping and subjective expert ratings of the impact of an activity. They felt that, no matter how small, every project should be viewed in a regional setting, so that the cumulative impacts likely to be missed in case-by-case appraisals would be identified. Relative levels of ecosystem sensitivity were assigned to each tract of land in the region by a team of scientists. Ecosystem sensitivity was characterized by three components: significance of the ecosystem regionally and globally, rarity or abundance of the ecosystem relative to others in the region or elsewhere, and resilience of the ecosystem. Determining ecosystem significance required evaluating its biological importance in terms of species composition, resource outputs, genetic reservoir, scientific value, and esthetic value. Ecosystem size and occurrence are the factors involved in evaluating rarity. The resilience of an ecosystem is a measure of a system's ability to absorb environmental stress without changing to a recognizably different ecological state. Each unit of land was rated at one of four sensitivity levels, from minimally sensitive to maximally sensitive. The sensitivity ratings were meant to provide information on the likely impact of an activity. Cooper and Zedler (1980) recognized that the use of an interdisciplinary team to evaluate ecosystem sensitivity was subjective; however, the degree of agreement attained among the team members suggested this was a worthwhile approach.

Another example of attempting to evaluate the importance of an ecosystem can be found in the Ecological Index method (Klopatek et al. 1980). It is based on the following:

1. identifying important ecological resources within the area,
2. determining the extent of those resources, and
3. computing the area quality value by creating a matrix which combines the magnitude of a particular resource and the importance of that resource.

The overall index is calculated using nationally available data on vegetation, avian species, mammalian species, and threatened and endangered species. The Ecological Index represents a hierarchical rating system in which all parameters are analyzed, using three levels of stratification: national, regional, and ecoregion section. The index filters information from one level to another. Although this index incorporates both habitat and species data, it lacks an aquatic component. However, it appears that such a component could be included with only slight modification.

The Wildlife Habitat Quality Index (USDA 1981) was described in the RCA 1980 Appraisal, Part II. Indexes of habitat quality, which reflect the overall value of habitat for a wide variety of vertebrate species, were developed for croplands, pasturelands, range lands, forest lands, wetlands, and aquatic areas (rivers, streams, and ponds). Availability of food and cover for wildlife was considered to be a function of land use. Weighted values were developed for several resources (e.g., forest lands, croplands) based on factors that contributed to habitat quality (e.g., grazed versus ungrazed forest). Wildlife habitat quality was estimated using data from the 1977 National Resource Inventories (USDA Soil Conservation Service 1977).[9] Water quality (e.g., nutrient levels, sediment loads) and minimum instream flow requirement data were considered to be essential for estimating quality of fish habitat. In addition to the water quality and water supply for farm ponds, the size and location of the ponds were considered important in limiting fish production. Estimates of fish habitat quality were made using data from the Second National Water Assessment (U.S. Water Resources Council 1978). Information on wildlife or fish species (e.g., presence or absence, relative abundance) was not included in this method.

Short[10] developed a technique whereby wildlife communities can be evaluated on the basis of vegetation structure. The physical strata in a cover type where a species feeds and/or breeds are used to classify the species into cells within a species-habitat matrix. The wildlife guilds that may occur in a cover type are determined by cluster analysis. Impacts on wildlife are then determined by examining the changes in the physical strata of the vegetation cover type. While the approach looks at species guilds, an index of total impact could be computed.

[9]USDA Soil Conservation Service. 1977. Erosion Inventory Instructions for County Base Data. Internal memo dated March 25, 1977. 7 p. Washington, D.C. Also, USDA Soil Conservation Service. 1977. Erosion inventory instructions for the PSU and point data collection. 20 p. Internal memo dated June 1977. Washington, D.C.

[10]Short, Henry. 1981. A technology for structuring, evaluating, and predicting impacts on wildlife communities. (Unpublished manuscript).

Interdisciplinary Team Approach

The use of a team of experts to estimate environmental indexes or assess environmental impacts has received much attention because of the difficulty in obtaining data (Suffling 1980) and the difficulty in quantifying ecosystem-level relationships (Cooper and Zedler 1980). An intuitive approach, such as a team of experts, relies on the experts to integrate their experience and the current knowledge to estimate the impact of management on the ecosystem under a wide variety of situations. Intuitive approaches have been used to estimate environmental variables not easily quantified and to estimate environmental variables which there is insufficient time to measure.

Examples of the first situation include the estimation of ecosystem sensitivity proposed by Suffling (1980) and the regional environmental assessment process proposed by Cooper and Zedler (1980). Another example would be the qualitative estimates of the 12 resource outputs in the FRES study (Kaiser et al. 1972). Among the estimated resource outputs were air quality, soil stability, rare and endangered species, depressed area impact, soil quality, and flexibility for future management.

An example of the second intuitive approach would be the forest planning process in the National Forest System. There, a team of experts, referred to as the interdisciplinary team (ID team), must develop a management plan for a forest. The plan must ensure coordinated planning among outdoor recreation, range, timber, watershed, wildlife, fish, and wilderness opportunities.

Where quantitative estimates of the ecosystem's responses to management are necessary, the ID team is directed to be as quantitative as possible. Where quantification is not possible, the following guidelines from Forest Service Manual (FSM 1920) are given.

For any action taken within the planning process that must rely on assumptions (or statistical inference) in lieu of specific data or information, the responsible official and the interdisciplinary team shall:

1. Identify the specific analytical technique and associated assumptions used.
2. Document why particular assumptions were used.
3. State the basis upon which the analytical techniques and corresponding assumptions were selected and the advantages and disadvantages compared with the relevant state-of-the-art techniques.
4. Ensure and document, to the extent practicable, the consistency of assumptions with those used in other land and resource management planning efforts, including the national program.
5. Assess the consequences and implications of using the assumptions.

The team approach appealed to Cooper and Zedler (1980), especially when the team members had a strong consensus in their estimations. Cooper and Zedler (1980) said that mathematical models in resource management do not adequately synthesize the appropriate information for impact assessment. They indicated that current models estimate the effects of environmental change on the productivity of ecosystems, but are less successful in predicting shifts in species composition of plant and animal communities, particularly terrestrial communities. Intuitive approaches integrate the person's experience and knowledge in a way that is not easy to track, but that may fill some gaps that are unavoidable in forest planning or research.

Simulation Modeling

Model Building

Simulation refers to mathematical and statistical models that have been implemented on a computer. Their use in ecology and resource management has greatly increased in the past 15 years. The process of constructing a simulation model can be broken into five stages: conceptual, diagrammatic, mathematical, computer programming, and validation/verification.

In the conceptual stage, the modeler's experience and intuition suggests important features about the system's structure to be modeled, given the questions being asked about the system. In the diagrammatic stage, word models and diagrams are used to structure the model. The most commonly used diagrammatic model is the "box-and-arrow" diagram, or the compartment diagram. There, boxes represent components or compartments of an ecosystem, and the arrows show inputs to and outputs from each compartment (fig. 1). Inputs to a compartment coming from outside the ecosystem are referred to as forcing functions, or driving variables, or exogenous variables. State variables refer to the contents of the boxes, and the parts of the system they represent. The choice of which parts of the system to model as state variables is made in the conceptual stage.

The complexity represented in the diagrammatic model is referred to as the degree of aggregation. Because a model never can completely replicate the system, compartments of the real system may be combined in the model. One example would be combining all plant species into one compartment instead of modeling each plant species.

In the mathematical stage, the structure and function of the ecosystem are described in equations. The relationship between state variables and/or flows is determined from experimental work, previous models, or the modeler's intuition. For example, the growth of a plant (state variable) could be represented as a function of sunlight, temperature, and precipitation, all driving variables, where the function was determined from field research.

The fourth stage in the modeling process is the computer programming stage where the mathematical equations are written into a computer program. The internal logic of the computer program is checked.

The last stage in the modeling process is the validation/verification stage. The model is tested under a variety of situations. An error analysis may be performed to determine the magnitude of error propagation in the model. A sensitivity analysis may be performed to determine how sensitive the model is to changes in the parameters of the equations. And, finally, the model output is com-

pared with different field data that were not used in constructing the model to determine how well the model mimics the real world.

The modeler's perceptions about the ecosystem affect the internal structure of the simulation model. Energy flow has been used to connect all ecosystem interactions in some models, while nutrient cycling has been used in others. Some models focused on population fluctuations, others concentrated on the dynamics of one animal and its environment. Environmental boundaries may be relatively small, as in the algal-fly community of a hot springs (Wiegert 1977), or large, as in the world resource production and consumption of the world (Meadows et al. 1972). The mathematical equations in the model may be based on years of research, as in the model of nutrient cycling in a *Liriodendron* forest (Shugart et al. 1976), or they may be based on empirical relationships where the theoretical underpinnings from research are lacking.

The various modeling approaches differ in terms of the type of mathematics used to describe the ecosystem. Differential equations and difference equations have been used in simulation models of energy flow, nutrient cycling, and population dynamics. Some algebraic models have been constructed also. Penning de Vries (1976) noted the increased acceptance of the state variable approach as a basic element of the simulation of continuous systems. Other modeling approaches have been reviewed by Van Dyne and Abramsky (1975), Holling (1978), and Shoemaker (1977).

Applications of Simulation Models

Van Dyne (1980) reviewed the development of simulation models, in the context of a review of systems ecology. The term "systems ecology" refers to the "ecology (which) deals with the structure and function of levels of organization beyond that of the individual and species" (Odum 1964). Van Dyne (1980) presented the following characteristics of systems ecology:

1. consideration of ecological phenomena at large, spatial, temporal or organization scales;
2. introduction of methodologies from other fields that are traditionally unallied with ecology;
3. an emphasis on mathematical models;
4. an orientation to computers, both digital and analog devices; and
5. a willingness to develop hypotheses about the nature of ecosystems.

The application of simulation models in ecology has been an integral part of the development of systems ecology. Some of the earliest applications of ecosystem simulations were those of Odum (1960) and Olson (1963) on an analog computer, and Garfinkel (1962) on a digital computer (Wiegert 1975). Since these attempts, simulation modeling has diversified greatly. Simulation models of ecosystems range from large, complex systems of equations to small sets of differential equations.

Models constructed for natural resource management differ in structure from modeling approaches in ecological simulation. This difference was pointed out by Spofford (1975) for aquatic systems models and Reed and Clark (1979) for forest growth models. Spofford (1975) contrasted the water quality models, based on the Streeter-Phelps approach which predicts dissolved oxygen or algal concentrations, with aquatic ecosystem models which predict trophic levels and species populations. He noted that the biological mechanisms were more complex in the models of aquatic ecosystem than in the water quality models. The latter models were also based on relationships which were more empirical.

Applications of simulation modeling vary greatly; in most cases, the simulation model was built for a specific ecosystem, and often for a specific set of management problems. Van Dyne and Abramsky (1975) compiled a list of models used in agricultural and natural resource fields, including both simulation and optimization models. Weigert (1975) and Frenkiel and Goodall (1978) reviewed the development of simulation modeling and critiqued simulation model building. H. T. Odum (1971) and Holling (1978) presented modeling frameworks and several case examples. Potential users of simulation models need to critique carefully the assumptions underlying the simulation models. As Odum (1976) noted, no theoretical framework previously existed to guarantee the same structure in each ecosystem model.

Summary

The type of analytical technique used to determine the impact of management depends on the problem and the resources available. Where a diversity of management impacts or alternative sitings of one impact are examined, an intuitive approach, such as the ID team approach, has been found most useful (Cooper and Zedler 1980). Where one specific management activity or ecosystem is examined, a quantitative approach, such as simulation modeling, has been found useful (Hall and Day 1977).

ECONOMIC ANALYSES OF PRODUCTION

In economics, a large body of theory has been developed concerning production analysis. This section contains a brief review of the general theory of production and the use of mathematical programming in production analyses of resource outputs.

Economic Theory of Production

The economic theory of production deals with problems of allocation and utilization of limited resources by individual firms. Firms are considered to be technical units which transform inputs into outputs (i.e., engage in production). Inputs are anything the firm utilizes in producing outputs. Outputs are the commodities the firm produces.

Single Output Production

The production process that specifies the maximum output obtainable from any combination of inputs is said to be technically efficient. A mathematical expression that relates inputs and outputs through technically efficient production processes is called a production function. Equation [1] represents a production function, f, for a production process involving one output, Q, and inputs $I_1, ..., I_n$.

$$Q = f(I_1, I_2, ..., I_n) \qquad [1]$$

Specific functional forms for f (both linear and nonlinear) are used in empirical estimation of production functions.

Starting with the production function as given, economic production theory assumes that firms behave in an optimizing fashion, and focuses on decisions made by the firm with regard to optimal levels of inputs and outputs. In the simplest case addressed by production theory, firms are assumed to operate in competitive markets for both inputs and outputs (i.e., input and output prices are taken as constant by the firms for all levels of inputs and outputs). The case for other types of markets is also considered in classical production theory. For a general discussion of economic production theory, see a standard microeconomic text such as Henderson and Quandt (1971).

The firm may have to make three general production decisions. First, it may seek to maximize output, subject to a fixed budget with which to purchase inputs. Second, it may seek to minimize the cost of inputs, subject to producing a given level of output. Third, it may seek to maximize profits where both budget and output quantities are variable.

In the first two cases, the marginal condition for optimization with two inputs in equation [1] is:

$$\frac{\partial f/\partial I_1}{\partial f/\partial I_2} = RTS = \frac{C_1}{C_2} \qquad [2]$$

where C_i = the factor price of the i^{th} input (I_i). The term on the left, the ratio of partial derivatives of the production function (which is the ratio of marginal products of the two inputs), is the rate of technical substitution (RTS). This ratio expresses the rate at which one input can be substituted for another in production and still obtain the same level of output. The term on the right is the ratio of input prices. The optimal level of production is found by equating the ratio of marginal products (RTS) to the ratio of input prices. This solution is shown graphically in figure 2.

In the third case, the more general problem faced by a firm is to maximize profits, allowing both budget and output levels to vary. Profit is equal to total revenue (PQ) less total cost ($C_1I_1 + C_2I_2$). By substituting equation [1] for Q in this expression of profit, the firm seeks to maximize:

$$\Pi = Pf(I_1, I_2) - C_1I_1 - C_2I_2. \qquad [3]$$

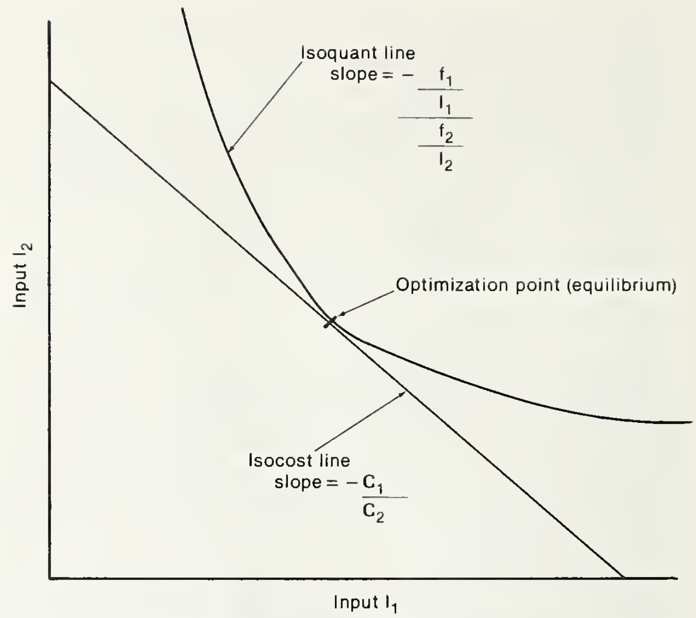

Figure 2.—Isoquant and isocost equilibrium.

Because the firm is a price taker in both the input and output markets, P, C_1, and C_2 are constants. The marginal conditions for profit maximization are:

$$P\frac{\partial f}{\partial I_1} = C_1 \text{ and } P\frac{\partial f}{\partial I_2} = C_2 \qquad [4]$$

On the left side of each equation, output price, P, is multiplied by the partial derivative of the production function (the marginal product). This term is the value marginal product (*VMP*) of input 1 or input 2. *VMP* shows the marginal rate of increase in revenue from using more of the given input. The terms on the right are input prices (C_1, C_2) and represent the rate of increase in total cost with additions of any input. The maximum profit level is found by equating the *VMP* of each input with that input's price.

Multiple Outputs and Joint Production

The general notation for multiple outputs and multiple inputs is given by an implicit production function:

$$f(Q_1, ..., Q_m, I_1, ..., I_n) = 0 \qquad [5]$$

where Q and I are vectors of outputs and inputs, respectively. Joint production exists "... whenever the quantities of two or more outputs are technically interdependent.... The production of joint products does not require an extended analysis unless they can be produced in varying proportions. If two products are always produced in a fixed proportion... the analysis for a single output can be applied" (Henderson and Quandt 1971).

With fixed inputs, a product transformation curve or production frontier is implied, such as the one graphically portrayed in figure 3 for two outputs. The mar-

ginal conditions for optimization in joint production for m outputs and n inputs require that:

1. the rate of product transformation between every pair of outputs must equal the output price ratio,
2. the rate of technical substitution between every pair of inputs must equal the input price ratio, and
3. the value marginal product of each input in production of each output must equal the input price.

Mathematical Programming

Mathematical programming is the term applied to a group of optimization techniques including linear programming, goal programming, integer and mixed integer programming, quadratic programming, geometric programming, and dynamic programming. All of these techniques are designed to select an optimal solution for a set of variables, often called activities. The optimal outcome is the numerical maximum or minimum of some specified performance criterion or objective function. This report will focus on linear programming as the state-of-the-art technique in applied mathematical programming, with a brief review of goal programming.

Linear Programming

Linear programming (LP) is a mathematical programming technique which can be used to maximize or minimize a linear objective function, subject to a set of linear constraints. A linear programming model has three major components:

1. The set of all possible activities under consideration. These are also called the choice variables, and make up the columns in the LP matrix, which is also called the A matrix.
2. The set of limitations on the resources needed to carry out the activities. These are called the constraints and, as linear combinations of the choice variables, make up the rows in the LP matrix. The sum of resources used by the activities must be constrained to the total resources available—often called the right-hand side or RHS.
3. The performance criterion for selecting the optimal set of activities from all possible activities. This objective function is a linear combination (weighted sum) of the choice variables, the weights being the numerical contribution of each to the objective function.

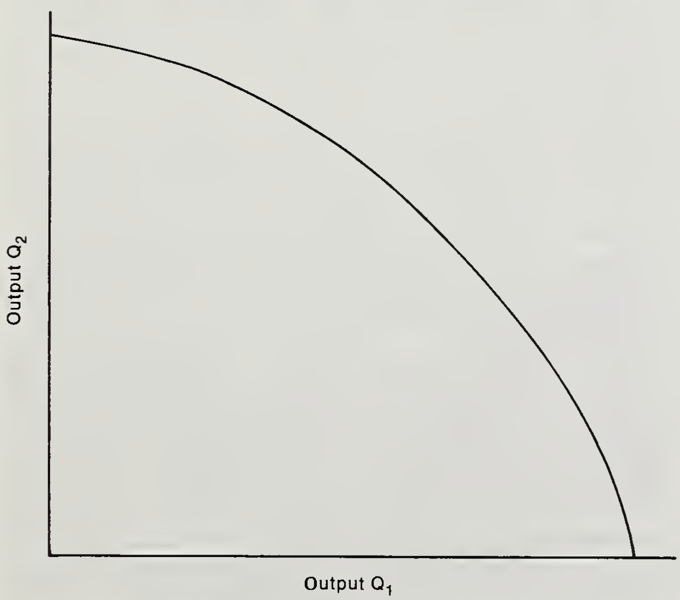

Figure 3.—Product transformation curve.

A simple representation of a linear programming problem follows:

Maximize:

$$Z = \sum_{j=1}^{n} C_j X_j \qquad [6]$$

Subject to:

$$\sum_{j=1}^{n} A_{ij} X_j \leq B_i \qquad i = 1 \ldots m \qquad [7]$$

$$X_j \geq 0 \qquad j = 1 \ldots n$$

In this example, there are n activities, and m constraints (rows). The total resource available for any row is B_i, and the amount of it used per unit of activity j is A_{ij}. Additionally, activities (X_j) may not take on a value less than zero. The problem expressed mathematically in equations [6] and [7] could be presented in matrix form in figure 4 for $n = 4$ and m = 3. The C_j are the objective function coefficients, indicating the marginal contribution of each X_j to Z.

X_1	X_2	X_3	X_4	type	RHS
A_{11}	A_{12}	A_{13}	A_{14}	$\leqq$	B_1
A_{21}	A_{22}	A_{23}	A_{24}	$\leqq$	B_2
A_{31}	A_{32}	A_{33}	A_{34}	$\leqq$	B_3
C_1	C_2	C_3	C_4		Z (Maximize/ minimize)

Figure 4.—A matrix representation of an LP problem.

Several assumptions are necessary for the mathematical solution of a linear programming problem. First, all mathematical relationships in both the objective function and the constraints must be linear in the choice variables. Nonlinear relationships can be piecewise approximated with combinations of linear functions. Linearity is assured by two requirements—proportionality and additivity. Each activity's contribution to the objective function and its rate of resource use is proportional to that activity; that is, coefficients in both the objective

(C_j) and constraints (A_{ij}) are constant for all levels of activity X_j. The total contribution to the objective function and the total resource use of two or more activities engaged in at the same time must equal the sum of the individual contribution, or resource use, of each activity engaged in separately. Second, all choice variables must be nonnegative. Third, all choice variables must be divisible; that is, they can take on fractional values. Additional constraints may be imposed on choice variables to ensure an integer value in integer or mixed-integer programming, which require different solution techniques than the general linear programming problem. Fourth, all coefficients (C_j and A_{ij}) must be specified before the model is run. Additionally, it is assumed these coefficients are known with certainty; thus, LP is a deterministic model. Fifth, only one objective function may be specified for maximization or minimization at any one time.

Although the LP formulation in equations [6] and [7] implies a lack of a time dimension, this is not a general limitation of LP. Discrete time periods can be incorporated by adding additional rows and columns for each time period. In this way, the LP can both allocate and schedule the activity variables. For a very readable discussion of linear programming applied to resource planning see Kent (1980).

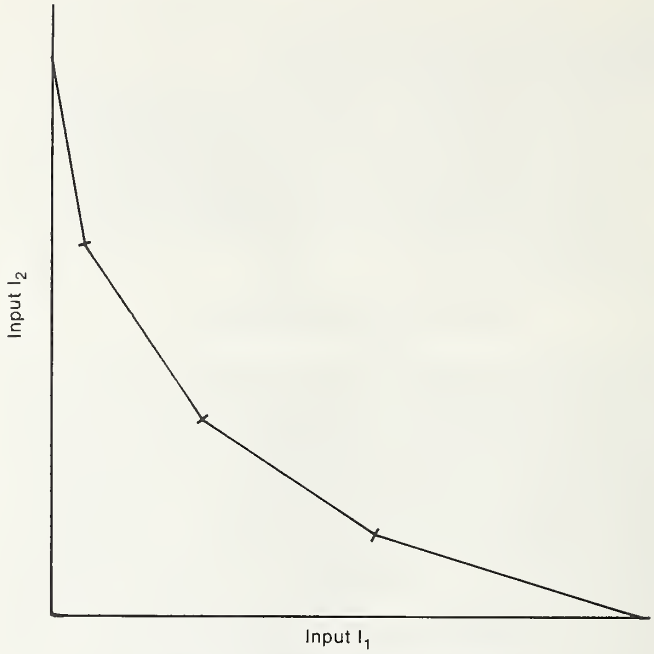

Figure 5.—Linear programming isoquant.

Figure 6.—Linear programming product transformation curve.

Linear Programming and Production Theory

A firm producing a single output may have several processes from which it can produce that output. A production process, represented by the columns in the LP matrix, utilizes the fixed resources (B_i) in some constant proportion (A_{ij}). This production process is of fixed proportions, divisible, and exhibits constant returns to scale (Dorfman, Samuelson, and Solow 1958). The firm chooses the optimal production process and the level of that production process. Because each process utilizes fixed resources at different but constant rates, substitution between sets of inputs can be accounted for by substitution between linear processes (i.e., between columns). A "kinked" isoquant results, as shown in figure 5 for two inputs (I_1, I_2).

Although the smooth marginal conditions found by calculus are not used in this "kinked" case, the same concepts of rates of substitution apply in the linear programming case. Substitution takes place between activities rather than directly between inputs.

The standard linear programming problem also can be interpreted for the case of joint production. Processes (columns) may exist for simultaneously producing more than one output. Because the resource level is fixed by the right-hand side, a production frontier can be traced out by allocating the available input to different processes and finding resultant output vectors. Such a production frontier is shown in figure 6 for two outputs. With this "kinked" production frontier, the concept of marginal rates of product transformation still apply to optimal decisions. In order to approximate the smoothly curved production frontier of production theory, it may be necessary to consider a large number of production process (i.e., a large number of columns in the LP matrix).

An important point is that linear programming generally starts one step before economic theory by choosing a technically efficient production process as well as an economically efficient one. In this sense, LP provides more information to a manager who is not aware in advance of technically efficient production processes. It can readily be used to show the implications of alternative choices. This aspect has made linear programming a widely used, practical tool for management and planning in the business sector.

History of Linear Programming Applications

Early Applications of Linear Programming to Forestry Problems

Some of the first applications of linear programming to forestry problems dealt with forest and wood industries. Paull and Walter (1955) and Paull (1956) applied linear programming to minimize delivery transportation costs and minimize trim loss in newsprint manufacturing. Bethel and Harrell (1957) used an LP to find optimum costs of alternative plywood production and distribution procedures. Jackson (1958) and Jackson and Smith (1961) used LP to determine optimal sawing methods in a mill. They formulated both a profit maximization and a production maximization problem.

Coutu and Ellertsen (1960) used LP to find the best (income maximizing) allocation of resources among various farming activities, including forestry. Some of the first scheduling applications dealt with minimizing the cost of providing pulpwood to a mill (Theiler 1959, Curtis 1962). The traditional forest regulation problem of maximizing volume subject to sustained yield constraints was formulated by Loucks in 1964. Kidd, Thompson, and Hoepner (1966) formulated the regulation problem to maximize present net worth subject to various management constraints. In 1967, Nautiyal and Pearse used LP to examine optimum harvest patterns, rotation length, and the conversion period.

In all of these early applications, the LP's were developed for each specific problem. In 1971, a linear programming package (Timber RAM) was developed which could be applied to various timber management planning problems (Navon 1971). For a more technical discussion of Timber RAM, see Alig et al. (1983). Prototype RAM models for range and transportation systems were developed later (Jansen 1976), but not widely used.

Although the inputs and outputs of Timber RAM are timber related, Navon (1971) suggested that the model could partially evaluate the "interaction of range, watershed, recreation, wildlife, and timber management policies." This was accomplished largely by excluding land from the allowable cut base and by meeting constraints imposed by commitments to produce other resources through reduction in wood yield.[11] Chappelle et al. (1976) argued that this approach to multiple-use considerations does not necessarily provide an optimal solution to forestry (as opposed to timber) planning problems.

This incremental approach to multiple-use modeling (i.e., starting with a timber model and then modifying it) appears to have precedent in the way functional planning evolved toward multiple-use planning in response to the Multiple Use-Sustained Yield Act of 1960. According to Hall (1963) multiple use was initially viewed as a problem of coordinating separate resource programs rather than starting with an overall multiple-use program. Hall suggests this approach can be explained by history:

> Forest managers have had long experience in planning for particular resources, especially timber. Multiple use objectives are currently being superimposed on the older procedures.... foresters are accustomed to working with the traditional tools and concepts of timber management and probably the easiest way to obtain multiple use objectives is by building on this base.

Goal Programming

Goal programming is a mathematical programming technique that can be used to find a solution to a resource allocation problem involving several objectives, subject to a set of linear constraints. Depending on the type of formulation, all goals may be considered simultaneously in a composite (and single) objective function, or sequentially in a series of objective functions. Goal programming is a particular form of linear programming where the choice variables are deviational variables—showing over- or underachievement of the specified goal levels of output. For a more formal discussion of goal programming, see Lee (1972).

Goal programming concepts were developed by Charnes et al. in 1955 and applied widely to management problems in the business sector. Field (1973) introduced goal programming to the forestry literature. Bottoms and Bartlett (1975) applied goal programming to multiresource management of 9,050 acres of the Colorado State Forest. Their formulation used ordinal priority ranking of goals.

Bell (1976) further discussed transformation of a linear program into a goal program with a composite weighted objective function. Dane, Meador, and White (1977) used the composite weighted objective form of goal programming on a 158,000-acre planning unit on the Mt. Hood National Forest, Oregon. Schuler, Webster, and Meadows (1977) reported on their pilot application of goal programming on a 10,000-acre subunit of the Mark Twain National Forest, Missouri.

Schuler, Webster, and Meadows (1979) suggested the biggest problem in the application of goal programming involved the technical coefficients. Steuer and Schuler (1978), in a discussion of the same pilot study pointed out further problems, encountered in goal ranking:

> The objectives [goals] were also ranked by the planning team. However, the ranking was strictly ordinal. A cardinal ranking scheme was considered to be unobtainable. This constituted the first noticeable beginning of the series of difficulties that occurred in trying to find an OR/MS technique to solve this forest management problem.

Dyer et al. (1979) used the Bottoms and Bartlett goal program to show the sensitivity of the goal programming allocation to changes in priority levels and concluded that an ordinal ranking goal programming would not solve the problem of determining objective function weights required to achieve a pareto optimum allocation of resources. Dyer et al. (1979) also discussed the use of goal programming as a suboptimization technique; they

[11] *Johnson, K. Norman. 1980. Timber activity scheduling on the national forests: The second revolution. Paper presented at Oregon State University seminar, Corvallis.*

concluded it is a useful tool if used carefully and with a complete understanding of its inner workings.

INTEGRATED APPROACHES TO ANALYZING THE PRODUCTION OF NATURAL RESOURCES

A single theoretical basis for integrated analysis across disciplines does not exist today. Theoretical developments attempting to provide this theoretical basis include Georgescu-Roegen (1977), Boulding (1977), Thompson (1977), and Odum (1971). Odum (1978) uses energy to integrate ecological, economic, and social systems. Applications in regional planning can be found in Kemp et al. (1977) and Boynton et al. (1977). The difficulties of determining the value of energy in this approach have been discussed by Hyman (1980).

Holling (1978) developed an approach incorporating a quantitative description of system behavior using catastrophe theory, and a qualitative integration of system behavior using workshops. The workshops have been used to bring together the academicians, who mathematically describe the system, and the managers and politicians, who manage the system. The feedback between managers, politicians, and academicians facilitated a deeper understanding of the system and its model. Applications in land planning can be found in Holling (1978).

The dominant technique in integrating ecological and economic analyses is the optimization modeling approach. These models can analyze the tradeoffs between a variety of resource production alternatives. The decision criteria for the tradeoff analysis can be varied also. This type of analysis presumes the input of benefit/cost information and production capability/response information.

Linear Programming Multiresource Management Problems

Perhaps the most successful applied attempts at integrating information across disciplines and resources have been the multiresource linear programming models. The first example of such a model was D'Aquino (1974). The basic structure of these models will be illustrated in a simplified linear programming model considering only two types of land, five management prescriptions, and three resources (fig. 7).

In figure 7, the major column headings are types of land and/or resources. The "X_j's" under the two land types are the number of acres allocated to alternative management prescriptions which could be applied in TYPE I (X_1 and X_2) and TYPE II (X_3, X_4, X_5) land. X_1 through X_5 are choice variables defined as the number of acres allocated to the given management prescription (1 through 5).

The timber, wildlife, and forage rows in the matrix represent the resource outputs of this forest system which result from implementation of the management prescriptions. The land, TYPE I and TYPE II, rows are the inputs (acres) to this joint production system. K_5 acres of Type I land are available, and K_6 acres of Type II land are available.

The timber output, wildlife output, and forage output rows are the amounts of each of the outputs that are harvested from the forest system. The "Net Benefit" row is the objective which managers seek to maximize given the resources available and the production relationships involved.

The " X's" under the major column heading "Products" (X_6, X_7, X_8) are accounting columns which collect

	Type I		Type II			Products			Constraint type	RHS
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8		
Timber	$A_{1,1}$	$A_{1,2}$	$A_{1,3}$	$A_{1,4}$	$A_{1,5}$	$-A_{1,6}$			=	$K_1=0$
Wildlife	$A_{2,1}$	$A_{2,2}$	$A_{2,3}$	$A_{2,4}$	$A_{2,5}$		$-A_{2,7}$		=	$K_2=0$
Forage	$A_{3,1}$	$A_{3,2}$	$A_{3,3}$	$A_{3,4}$	$A_{3,5}$			$-A_{3,8}$	=	$K_3=0$
Budget	$A_{4,1}$	$A_{4,2}$	$A_{4,3}$	$A_{4,4}$	$A_{4,5}$				$\leqq$	K_4
Type I	$A_{5,1}$	$A_{5,2}$							=	K_5
Type II			$A_{6,3}$	$A_{6,4}$	$A_{6,5}$				=	K_6
Timber output						$A_{7,6}$			$\geqq$	K_7
Wildlife output							$A_{8,7}$		$\geqq$	K_8
Forage output								$A_{9,8}$	$\geqq$	K_9
Net Ben.	$A_{10,1}$	$A_{10,2}$	$A_{10,3}$	$A_{10,4}$	$A_{10,5}$	$A_{10,6}$	$A_{10,7}$	$A_{10,8}$		

Figure 7.—A simple resource allocation model where X_1 and X_2 are the number of acres in Type I land allocated to alternative management prescriptions; X_3, X_4, X_5 are the number of acres in Type II land allocated to alternative management prescriptions; X_6, X_7, X_8 are timber, wildlife, and forage products, respectively; the A_{ij} are production coefficients; the A_{10j} are the objective function coefficients; and the K_i are the right-hand sides (RHS).

or transform the outputs described in some of the rows into an aggregate output for the area being analyzed.[12]

The A_{ij}'s in columns one through five can generally be termed the impacts of the j^{th} management prescription on either the row outputs or row inputs. For example, $A_{1,1}$ is the output of timber per acre if the first management prescription is implemented, and $A_{5,1}$ is the amount of Type I land it takes to implement the minimum size prescription 1 treatment.

The coefficients in row 10, the "Net Benefits" row, describe the change in net benefits if one unit of the i^{th} management prescription occurs. Thus, $A_{10,1}$ is the cost of prescription 1 and $A_{10,6}$ is the benefit derived from one unit of timber output (X_6).

K_4 is an upper limit on the amount of money to be made available for managing the area. K_7 through K_9 are minimum levels of timber, wildlife, and forage that are required.

This simple model ignores time dimensions and other complexities such as nonconstant benefit coefficients. Environmental quality indexes are also excluded from the example. These complexities do not pose severe analytic problems, and they can be brought into the analysis without conceptual difficulty—though such a model would be significantly larger (i.e., more rows and columns).

Multiresource Models

The CARD-USDA Agricultural LP Model

Linear programming models are well suited to evaluating the response of agricultural production to changing policy or economic perturbation on both an intraregional and interregional basis. A model designed to do this has been constructed and tested by the Center for Agricultural and Rural Development (CARD) at Iowa State University in cooperation with USDA Soil Conservation Service and the USDA Economics, Statistics, and Cooperatives Service.

Given regional and national demands for land, water, fertilizer, and pasture, together with the quantity of resources available for use in satisfying them (i.e., constraints), the CARD-USDA model can minimize the cost of producing those demands. As such, the model can be used to assess the effects of initiating new markets, changing demands and resource availabilities, modulating costs, and altering the interaction of commodity production, resource purchase, and land development activities with the relevant markets.

The CARD-USDA model was delineated regionally in several ways. On the basis of soil type and management attributes, 164 land resource regions were defined. On the basis of production (crops and water) 105 separate producing areas were defined. Additionally, producing areas were agglomerated into 28 major marketing regions with a market center defined for each. Transfers of resources and demands between regions were at the marketing region level.

[12] *K_1 through K_3 are set at zero to force all product output levels into X_6, X_7, and X_8.*

RCS-RAA

In 1972, a system of interrelated computer programs was developed by the USDA Forest Service Watershed Systems Development Unit in Berkeley, Calif. The Resources Capability System (RCS) was designed to be "used to quantitatively evaluate functional programs as they relate to the basic soil, climatic, and water resources. This information can then be combined in the system with quantitative data from the various disciplines and functions of resource management, plus selected management objectives and constraints, and utilized in an interdisciplinary analysis of resource allocation alternatives" (USDA Forest Service 1972).

The Resources Capability System included several response simulation models (water yield, sediment yield, individual renewable resource models, and an economic analysis model) and a multiple resource allocation model. This allocation model became known as the Resource Allocation Analysis (RAA) component. It was this RAA component of RCS which received most of the attention during the mid-1970's. It included an LP model, its associated A-matrix generator, and its output display programs.

The RAA was first applied to water resource and river basin development planning. By 1975, it had been used on approximately 40 land-use planning problems in the USDA Forest Service National Forest System. Most of the forests using the RAA for multiple-use planning were in the West (Beaverhead, Nezperce, Montana; Williamette, Oregon; Modoc, Klamath, Shasta Trinity, California; and Payette, Idaho). The set of computer programs was continually modified in response to user needs in these various applications (Lundeen 1975).

The matrix generator, called MAGE5, was perhaps the most unique and notable aspect of the RAA package. A versatile, user-specified model, it included delineation of constraints, costs, benefits, and a single objective function. The output of goods and services could also be time-streamed; that is, outputs resulting from the application of management prescriptions could vary over time. The same could occur for rates of capital and labor inputs pertaining to resource management. In addition to the time-streaming option, the production of timber could be simulated with a user-specified growth function. This was one of the first examples of a coupling between simulation and optimization models even though the former was self-contained in the latter. The developers had planned to provide for additional simulation models as a way to quantitatively describe resource interactions; however, this was not fully accomplished.

The specification of the objective function in RAA allowed for flexibility. The user could specify any of the commodity or economic rows (or any combination of them) as an objective function (Lundeen 1975). Although it was possible to minimize costs, the most commonly used approach was to maximize present net worth or one of the major commodities. The LP was designed to be run iteratively with changing objective functions or different right-hand side constraints.

Overall, the RAA was user-operated and controlled. For example, the three main components of RAA (LP

model, matrix generator, report writer) could either be operated as a sequential, interfaced system, or as separate programs in order to aid in accomplishing other RCS objectives. Additional information on RCS can be found in USDA Forest Service (1972) and Dyrland (1973).

FREPAS

The FREPAS (Forest-Range Environmental Production Analytical System) model was developed as part of the Forest-Range Environmental Study (FRES), during 1970-72. The purpose of this study was to collate information about United States rangelands and to develop a technology for evaluating such information in a way that would serve the planning needs of the USDA Forest Service (USDA Forest Service 1972b). The analytical system was to permit the manipulation of various economic, political, and social constraints on the use of different range resource units in order to determine optimal management procedures.

The FRES model was a multiresource LP model with a cost-minimization objective function. Required model inputs included a nation-wide forest and range land inventory. For each land unit, the following inputs are required: then current (1970) management strategies, and associated resource outputs, maximum potential of resource production, and minimum level of management for each land unit based on legal restrictions. The data base for these inputs was developed as part of the FRES study. Computer programs for data manipulation, matrix manipulation, LP solution, and a report writer were developed (Kaiser et al. 1972). The FRES model was run under a series of policy alternatives (e.g., budget and resource production constraints), and the results, in terms of resource outputs, were compared with the then current (1970) situation (USDA Forest Service 1972b).

FRES defined a framework for land inventory. Thirty-four soil-vegetation units, based on Kuchler's (1964) classification system of potential natural vegetation, formed the foundation for land classification across the 48 coterminous states (Garrison et al. 1977). Each soil-vegetation unit, or ecosystem, was further divided by productivity (four classes) and condition (three classes). On forest ecosystems, productivity was defined by capacity to produce wood, and condition was defined by the stocking level of poles and sawtimber. On nonforest ecosystems, productivity classes were assigned according to relative herbage production compared to the maximum potential of that ecosystem. Condition classes followed the concepts supporting the USDA Forest Service definition of range condition (i.e., vegetative composition and vigor, soil erosion, and erosion-potential factors).

In addition to partitioning on the basis of potential vegetation, production, and condition, land was further divided according to ownership. Three ownership categories were recognized: (1) National Forest System, (2) other federal, and (3) nonfederal. As a result of the above partitioning, 1,224 unique combinations (called resource units) of ecosystem-productivity-condition-ownership were possible. Of these, the task force obtained and evaluated data for 956 resource units (USDA Forest Service 1972b).

The resource output production under different management strategies for each resource unit was determined by an interdisciplinary team of scientists. For each of six possible management strategies (table 1), a set of management practices were generated by the team. Resource outputs for each resource unit for each management strategy were also estimated by the team (table 2).

Table 1.—Management Strategies in FREPAS (USDA Forest Service 1972b)

Strategy A—Environmental management without livestock. Livestock are excluded by fencing, riding, public education, or incentive payments. Damage to the range resource is corrected to maintain a stewardship base. The range management cost is borne by other functions, such as timber.

Strategy B—Environmental management with livestock. Livestock is permitted at present capacity of the range environment. Investments are made only to maintain the environment at a stewardship level. Costs of correcting past abuse are charged to other functions.

Strategy C—Extensive management of environment and livestock. Management seeks full utilization of the animal unit months available for grazing. However, no attempt is made to maximize forage production by cultural practices.

Strategy D—Intensive management of environment and livestock. Production of forage is maximized subject to the constraints of multiple use. This strategy includes reseeding and complex livestock-management systems and practices.

Strategy E—Maximum management of environment and livestock. Livestock production is maximized, subject only to stewardship of soil and water resources. Multiple use is not a constraint.

Strategy X—Management at a substewardship level. Livestock are grazed at a level that depletes the range resource.

Table 2.—Resource outputs estimated for each resource unit in the FRES study (USDA Forest Service 1972b)

Output	Unit of measure
Grazing measures	
Browse and herbage	Tons per acre per year
Animal unit months	AUM per acre per year
Animal output value	$ per acre per year
Joint products	
Wood	Cubic feet per acre per year
Water	Acre feet per acre per year
Water quality	Acre feet per acre per year
Storm runoff	Inches per acre per year
Sediment	Tons per acre per year
Employment	Man hours per acre per year
Qualitative estimates	
Soil stability	A value between [1]1-5
Rare and endangered species	A value between 1-5
Nongame birds	A value between 1-5
Carnivores and raptors	A value between 1-5
Air quality	A value between 1-5
Soil quality	A value between 1-5
Depressed area impact	A value between 1-5
Cultural heritage, resident	A value between 1-5
Cultural heritage, nonresident	A value between 1-5
Beauty	A value between 1-5

[1]*A 5-point scale was used to measure qualitative products. The five points were:* 1 = bad, 2 = poor, 3 = fair, 4 = good, and 5 = excellent.

FREPAS, as an LP model, allocated acres of land to the various management strategies within each resource unit, subject to given resource product constraints, in order to minimize the investment cost for range management and treatment (Kaiser et al. 1972). The FREPAS model assumed a static environment, and did not allow for scheduling (i.e., the model ignored the effects of a decision's impact on opportunities during subsequent time periods).

NIMRUM

The National Interregional Multiresource Use Model (NIMRUM) is one of the four models in the National Interregional Multiresource Analytical System (NIMRAS) which was developed for the 1980 RPA Assessment. The purpose of NIMRAS was to help evaluate alternative national programs of forest and range land management. The models were summarized by Ashton et al. (1980) as follows:

> The National Interregional Multiresource Use Model uses linear programming to allocate national and regional demands for renewable resource uses on the land base. This model minimizes operational costs of alternative programs while achieving environmental restraints, range production, sustained wood yield, and wilderness.
>
> The second model evaluates regional employment and earnings triggered by a national program.
>
> The third model, Futures Foregone, keeps count of future options lost in terms of the amount affecting citizens groups, rate of impact, and length of impact.
>
> The last model, Social Conflict, operates on the postulate that there will be proponents and opponents for any resource use and that some degree of conflict is inevitable. The model uses impact information including that generated from previous models and serves to quantify the amount and pattern of conflict.

NIMRUM is a linear programming model which seeks to minimize the cost of allocating the nation's forest and range land base to alternative resource management activities, so as to meet expected demands for the various outputs. Ashton et al. (1980) explained NIMRUM this way:

> Each allocation is a pattern of resource uses that satisfies demand projections for certain market and nonmarket outputs. In this sense, the demand for goods and services is the driving force of the model. Costs are calculated for each allocation, and these direct the model toward its goal, the selection of the least expensive resource allocation, and management pattern to meet demand.

NIMRUM was the first national-level land allocation model to account internally for resource interaction (joint production). Because of the size of the national model, computations were actually carried out on two subnational models—one for the East and one for the West.

The NIMRUM land base was stratified according to 107 Kuchler potential natural communities (PNC), four ownership categories, four productivity categories, and four condition classes. The ownership categories were: National Forest System lands (NFS), Bureau of Land Management lands, other federal lands, and state and private lands. There were four productivity and four condition classes. As a result of the above partitioning, approximately 5,000 unique combinations (Resource Units) of ecosystem-productivity-condition-ownership were possible. These Resource Units (RU) were assumed to exhibit homogeneous response to management.

For each RU, the resource outputs under different management were determined by an interdisciplinary team of scientists. In FREPAS, only management strategies associated with range were defined (table 1). In NIMRAS, appropriate combinations of management levels for range, wildlife, and timber representing current use were made by the ID team for each RU. Thus, for example, a combined management level to "do nothing" consists of: range management A—environmental management without livestock; timber management level 1—no commercial use; and wildlife management level 1—no management. Each combination, called a management triplet, had a set of management practices associated with it. Six management levels, similar to the six strategies in FREPAS, were possible for range. Six management levels for timber and three management levels for wildlife were defined. Table 3 lists the resource outputs in NIMRUM.

Table 3.—Resource outputs in the NIMRUM model (Ashton et al. 1980)

Output	Unit of measure
Herbage and browse production	Pounds per acre per year
Net wood growth	Cubic feet per acre per year
Wood harvested	Cubic feet per acre per year
Domestic livestock grazing	AUM per acre per year
Wild ruminant grazing	AUM per acre per year
Dispersed recreation use	Visitor-day per acre per year
Water yield	Inches per acre per year
Storm runoff	Inches per acre per year
Sediment yield	Tons per acre per year
Life form—water	Percent of area
Life form—ground	Percent of area
Life form—bushes	Percent of area
Life form—trees	Percent of area

Resource management practices are the basis for NIMRUM costs. Costs of the individual resource management practices were aggregated into single resource management levels, and the cost of the management level for timber, for range, and for wildlife were added to generate total costs for the management triplet. Costs for all ownerships were assumed to be similar. Range costs were based on Forest Service budget data, and timber costs were based on the Forest Service Timber Management Practice Cost Survey conducted in 1976. Wildlife costs were drawn from timber or range costs, depending on the type of vegetation manipulation undertaken for habitat management. All costs were annual averages based on a 50-year time period. Capital costs

(consisting chiefly of roads) with relatively long lives were discounted at 6-5/8%. Other costs were not discounted.

Pickens[13] noted that the objections to NIMRAS were the result of a lack of faith in the input data. While he acknowledged that there are problems with the data, the use of an ID team to generate such a national data set was considered the most viable approach to give the best possible data with the time and resource constraints imposed on the development of NIMRAS. Some of the information required in the analysis was not available from scientifically conducted studies, reflecting the functional approaches taken in previous studies on management implications. He stressed that, for NIMRAS, the data was sufficiently accurate to measure the type of responses they were commissioned to study. Further uses of the model should examine the data quality problem.

FORPLAN

The Forest Planning Model (FORPLAN) is intended for use on every national forest (or groups of national forests) in the USDA Forest Service National Forest System. It is one of the analytical tools to be utilized in fulfilling the requirements of the National Forest Management Act of 1976 and its subsequent regulations.

FORPLAN is a software package that serves as a matrix generator, an interface to the Univac 1100 FMPS[14] linear programming (LP) solution algorithm, and a report writer of the LP solution. The type of LP which FORPLAN creates varies considerably according to application by the user on any given forest. Many options are available in the FORPLAN package—a characteristic that is consistent with the widespread application intended. In general, the LP which FORPLAN generates is intended to simultaneously solve management activity scheduling problems, land allocation problems, and output mix problems. The basic structure is much like the simple example given previously, with the addition of scheduling capabilities. Because FORPLAN evolved from a timber model called MUSYC, it retains some emphasis on timber analysis capabilities; however, the emphasis in application is up to the user rather than the software package itself.

The responsibility for determining alternative management prescriptions to be applied within the forest and for quantifying the ecological impact of those management prescriptions rests with the interdisciplinary team (ID team). Because this information is forest-specific, the experience of the team members on site becomes very important. In order to present the general flavor of FORPLAN capabilities, some of its more important options/characteristics are briefly discussed in this section. For a comprehensive discussion of FORPLAN, see Johnson et al.[15]

Perhaps most basic to the configuration of any LP generated by FORPLAN is the definition of analysis areas (AA's), analogous to RU's in NIMRUM, and the alternative management prescriptions for each analysis area. FORPLAN allows considerable flexibility in the user designation of analysis areas and management prescriptions. Analysis areas are identified by three user-specified land characteristics (up to 60 categories of each), up to 9 working groups, up to 15 land classes, and up to 60 existing vegetation classes. Every alternative management prescription specified in FORPLAN must apply to a given analysis area. In addition, alternative prescriptions can be included to apply to the regeneration classes created by prescriptions with harvest practices. The time frame that applies to management prescriptions as well as to resultant outputs is also quite variable, having up to 30 time periods of 1 to 20 years each.

Also basic to the structure of any LP generated by FORPLAN is an option called "Aggregate Emphasis." This option allows designation of groups of analysis areas that must be allocated to management prescriptions together. This restriction is to avoid illogical situations such as "an analysis area allocated to intensive timber management production in the midst of analysis areas allocated to a wilderness".[15]

The structure of any FORPLAN-generated LP is also subject to area and volume control, harvest flow (e.g., nondeclining yield), ending inventory, management emphasis and intensity, and cultural treatment constraints. These kinds of constraints can take on numerous configurations.

Concerning timber harvest (and other timber activity) scheduling, FORPLAN can construct an LP based on either of two structures (Johnson and Schnerman 1977) which differ in the manner in which they define timber choice variables and handle multiple harvests within the planning horizon. Model I is more conducive to keeping track of location on the ground, while Model II is more conducive to minimizing model size.

FORPLAN has options for 10 different objective functions in the LP it generates:

1. Maximize PNW for n periods—maximize discounted present net worth (net monetary income) over n periods under the assumption that the amount of output provided does not affect its price.
2. Minimize cost for n periods—minimize undiscounted monetary cost over n periods.
3. Minimize discounted cost for n periods—minimize discounted monetary cost over n periods.
4. Maximize PNW under downward-sloping demand for n periods—maximize discounted net income over n periods under the assumption that the amount of output offered influences the price received.

[13] *Pickens, James B. 1980. NIMRAS system documentation. (Unpublished report prepared for USDA Forest Service, Washington, D.C.).*

[14] *The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.*

[15] *Johnson, K. Norman, Daniel B. Jones, and Brian M. Kent. 1980. Forest planning model (FORPLAN) user's guide and operations manual. (Draft). USDA Forest Service Land Management Planning, Fort Collins, Colo.*

5. Maximize PNB under downward-sloping demand for n periods—maximize discounted net benefit (approximately the discounted sum of producer's plus consumer's surplus) over n periods, under the assumption that the amount of output influences the price received.
6. Minimize deviations from goals—minimize the penalty incurred through nonachievement of the goals specified.
7. Maximize output *i* for n periods—maximize one of the scheduled or nonscheduled outputs over n periods.
8. Minimize output *i* for n periods—minimize one of the scheduled or nonscheduled outputs over n periods.
9. Maximize PNW for individual stands—specifying this objective function produces a report giving the maximum discounted net income (PNW) over the planning horizon projected for each analysis area containing timber available for harvest, considering each prescription and possible time of entry and harvest.
10. Maximize PNW for individual stand with detail—specifying this objective function produces a report giving the maximum PNW for each analysis area containing timber available for harvest, as done under objective 9. It also produces the PNW for each prescription designated for each analysis area, considering all possible times of entry and harvest.

For objective functions 4 and 5, FORPLAN can generate a piecewise approximated downward-sloping demand curve for timber. Fixed prices are assumed for all other outputs. At this time, costs can be assigned per acre for timber-related management prescriptions and per unit output for all outputs (including timber). It is anticipated that the capability to assign costs per acre for all management prescriptions will soon be available in FORPLAN. An option to include fixed costs is also available in FORPLAN.

Output constraints or output targets are an important part of the LP models generally developed with FORPLAN. These targets set minimum or maximum levels of outputs to be obtained in the LP solution and literally drive the model in some instances. Inclusion of these targets is directly mandated by the NFMA regulations.

CONCLUSIONS

Optimization models provide a method to integrate the ecological, economic, and social impact analyses, and to identify opportunities based on selected criteria. The predictions from simulation models can be used as input for the optimization model. Specifically, the supply/demand models can provide the benefit/cost (economic) information, and the ecological analyses can provide the production capability/response information for the optimization models. The social analyses can predict social impacts of the solutions provided by an optimization model. Public participation also provides social inputs. In integrating ecological, economic, and social analyses, optimization models can analyze tradeoffs between resource outputs and opportunities for improving the resource situation based on a variety of criteria.

The difficulty of scope remains, however. Modeling relatively small areas of land (such as a National Forest) is appealing because of the relative detail, resolution, and accuracy that can be achieved. However, regional and national concerns are different than local concerns and joint strategies between small land units may be highly desirable. The need for centralized decisionmaking is a primary motivation for national planning efforts such as RPA.

There are essentially three alternative approaches to this dilemma. First, a national model could be utilized, capturing whatever level of resolution possible. This is roughly the approach taken in the NIMRUM effort. Second, one could simply "add up" the results of small-scale models, such as FORPLAN. Third, a middle-ground solution would be a multilevel approach as outlined by Wong (1980).

Basically, the idea is to utilize models such as FORPLAN at the lowest levels of analysis and analyze only alternative output vectors at higher levels. That is, all production possibilities analysis occurs only at the lowest level, and the higher level models simply "choose" from the different possibilities that are determined to be feasible. This type of approach is discussed elsewhere in more detail as a possible assessment analysis tool.[16]

[16]U.S. Department of Agriculture, Forest Service. 1981. Problem analysis: Integrated resource analysis for national assessments. 150 p. Staff paper— National Resource Analysis Techniques Project, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

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This paper gives an overview of the analytical methods that have been used in integrated (multidisciplinary, multiresource, and multilevel) land management production analyses. The ecological and economic theory underlying both simulation and optimization methods are also reviewed.

Keywords: Integrated land management, multiresource production analyses

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Rocky
Mountains

Southwest

Great
Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526